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The Constrained E_6SSM at the LHC

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Based on:

P. Athron, S.F. King, DJM, S. Moretti, R. Nevzorov

arXiv:1102.4363, arXiv:0904.2169, arXiv:0901.1192

The E_6SSM

[S.F.King, S.Moretti & R. Nevzorov, Phys.Rev. D73 (2006) 035009 ; Phys.Lett. B634 (2006) 278-284]

“Inspired” by the gauge group E_6 , breaking to the SM via

$$E_6 \to SO(10) \times U(1)_\psi$$

$$\hookrightarrow SU(5) \times U(1)_\chi$$

$$\hookrightarrow SU(3)_C \times SU(2)_W \times U(1)_Y$$

where only one linear superposition of the extra *U(1)* symmetries survives to low energies:

$$U(1)_N = \tfrac{1}{4}U(1)_\chi + \tfrac{\sqrt{15}}{4}U(1)_\psi$$

This combination is required in order to keep the right handed neutrinos sterile.

So the E_6SSM is really a $SU(3)_C \times SU(2)_W \times U(1)_Y \times U(1)_N$ gauge theory.

Matter Content

All the SM matter fields are contained in one 27-plet of E_6 per generation.

$$\left[\,27\,\right]_i \Rightarrow \left[\,10,\ 1\,\right]_i + \left[\,5^*,\ 2\,\right]_i + \left[\,5^*,\ -3\,\right]_i + \left[\,5,\ -2\,\right]_i + \left[\,1,\ 5\,\right]_i + \left[\,1,\ 0\,\right]_i$$

$\left[\,10,\ 1\,\right]_i$	$Q_i,\ u^c_i,\ e^c_i$
$\left[\,5^*,\ 2\,\right]_i$	$L_i,\ d^c_i$
$\left[\,5^*,\ -3\,\right]_i$	$H_{1\,i} = \begin{pmatrix} H^0_{1\,i} \\ H^-_{1\,i} \end{pmatrix},\ \bar{D}_i$
$\left[\,5,\ -2\,\right]_i$	$H_{2\,i} = \begin{pmatrix} H^+_{2\,i} \\ H^0_{2\,i} \end{pmatrix},\ D_i$
$\left[\,1,\ 5\,\right]_i$	S_i
$\left[\,1,\ 0\,\right]_i$	N^c_i

3 generations of “Higgs”

exotic quarks

singlets

right handed neutrino

SU(5) reps.

$U(1)_N$ charge × √40

New exotic states and symmetries

- Only the third generation Higgs boson gains a VEV.
  The others are neutral and charged scalars - we call them **"inert Higgs"**.
  Three generations of singlets, with $\langle S_3 \rangle \neq 0$

- Extra U(1) $\rightarrow$ extra gauge boson, Z'.
  After EWSB this will become massive (after eating the imaginary part of S_3)

- Additional SU(2) doublets H' and $\bar{H}'$, relics of an additional $27'$ and $\overline{27}'$ which survive down to low energies, and are required for gauge unification.

- Z_2^B or Z_2^L symmetries to prevent proton decay (analogous to R-parity in the MSSM)
  $Z_2^B \Rightarrow$ D is a leptoquark $\qquad$ $Z_2^L \Rightarrow$ D is a diquark

- Approximate Z_2^H symmetry to evade large Flavour Changing Neutral Currents
  3rd generation Higgs and singlet superfields even, all other fields odd.
  Must only be approximate to allow exotic particles to decay.

The Constrained E6SSM

The E_6SSM has 43 new parameters compared with the MSSM (14 are phases).

But if we apply constraints at the GUT scale, this is drastically reduced.

Set: $$g_1(M_X) = g_2(M_X) = g_3(M_X) = g_1'(M_X)$$

soft scalar masses $\longrightarrow$ m_0

gaugino masses $\longrightarrow$ $M_{1/2}$

$$A_{\lambda_i}(M_X) = A_{\kappa_i}(M_X) = A_{t,b,\tau}(M_X) = A(M_X)$$

Important parameters: $\lambda_i,\ \kappa_i,\ h_t,\ h_b,\ h_\tau,\ m_0,\ M_{1/2},\ A$

We derived Renormalisation Group Equations, and modified SoftSuSY [Allanach, arXiv:hep-ph/0104145] to run down the GUT scale parameters to low energies.

- Gauge and Yukawa couplings (2 loop),
- Soft breaking gaugino and trilinear masses (2 loop),
- Soft scalar masses (1 loop).

$\mathrm{cE_6SSM}$ Particle Spectra

For most allowed scenarios $m_0 \gtrsim M_{1/2}$, so squarks tend to be heavier than the gluino

Neutralinos, charginos and gluino

$$m_{\tilde{\chi}_1^0} \approx M_1 \qquad m_{\tilde{g}} \approx M_3$$

$$m_{\tilde{\chi}_2^0} \approx m_{\tilde{\chi}_1^\pm} \approx M_2$$

$$m_{\tilde{\chi}_{3,4}^0} \approx m_{\tilde{\chi}_2^\pm} \approx \mu = \lambda\langle S\rangle$$

$$m_{\tilde{\chi}_{5,6}^0} \approx M_{Z'}$$

Higgs bosons

$$m_{h_1} \approx M_Z + \Delta$$

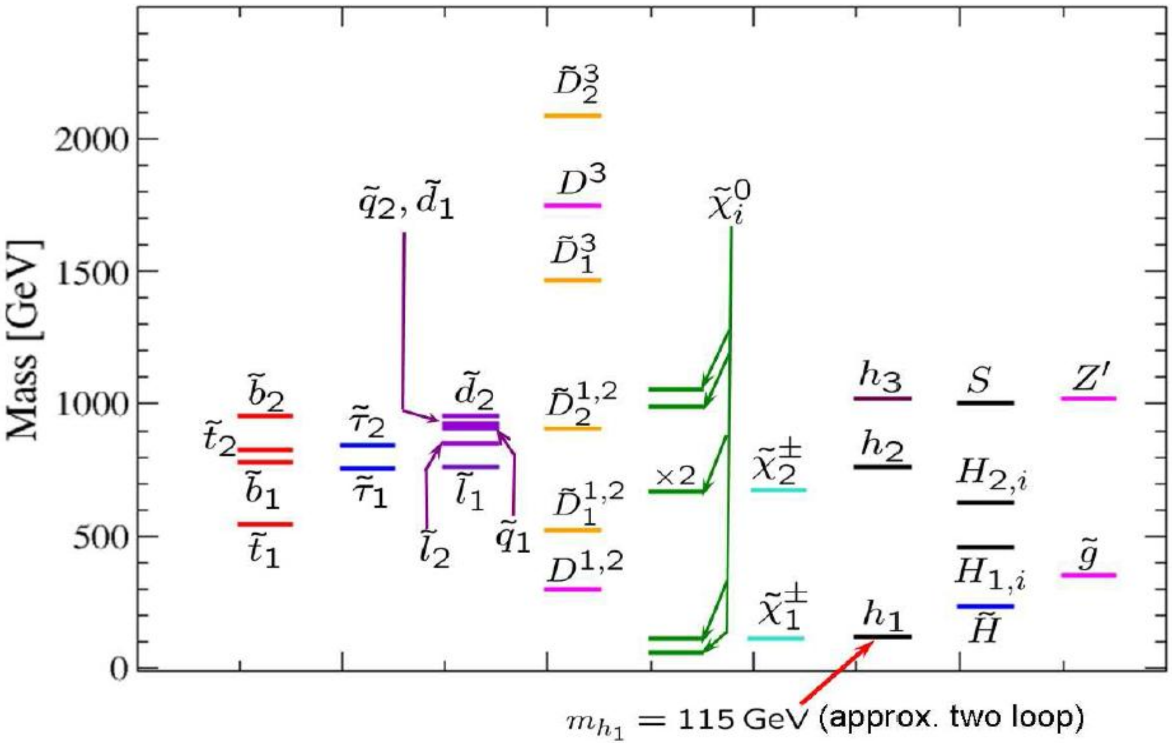
$$m_{h_2} \approx m_{H^\pm} \approx m_A$$

$$m_{h_3} \approx M_{Z'}$$

exotic quarks	$\approx \kappa_i\langle S\rangle$	
exotic squarks	$\approx m_{D_i}^2 + \kappa_i^2\langle S\rangle^2$	+ mixing and auxiliary D-terms
inert Higgs	$\approx m_{H_i}^2 + \lambda_i^2\langle S\rangle^2$	+ auxiliary D-terms
inert higgsino	$\approx \lambda_i\langle S\rangle$	

"Early Discovery" Benchmark C

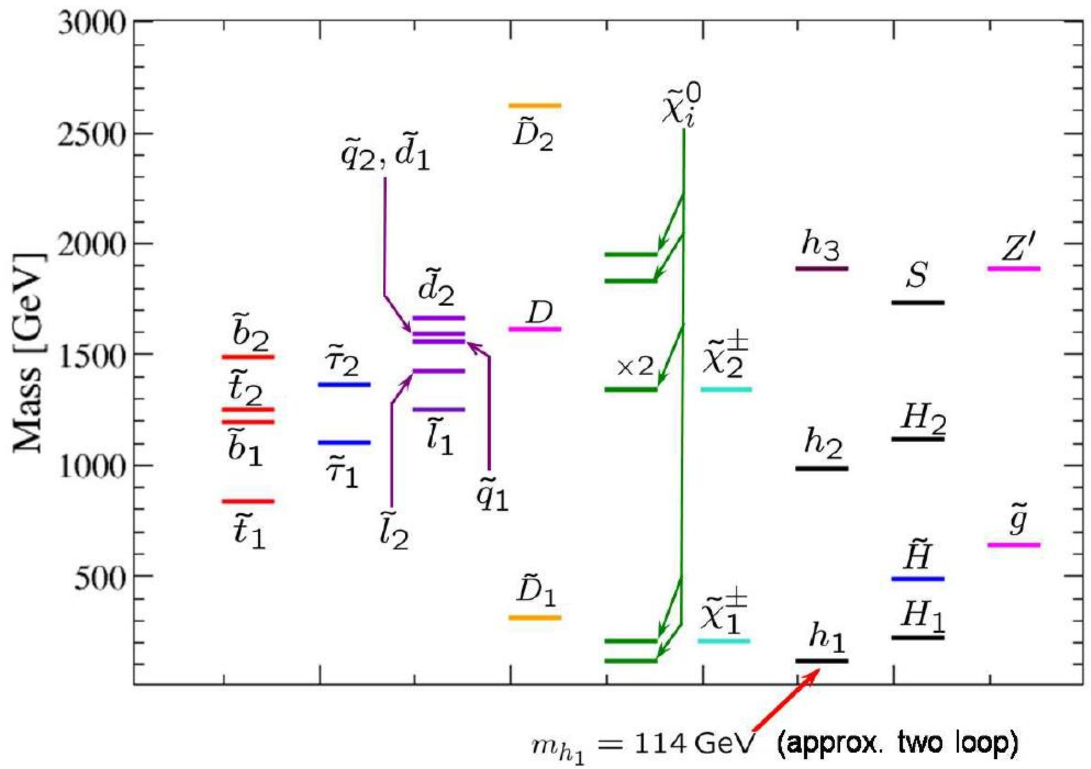
$$\begin{aligned}
\tan\beta &= 10\\
\lambda_3(M_X) &= -0.378\\
\lambda_{1,2}(M_X) &= 0.1\\
\kappa_3(M_X) &= 0.42\\
\kappa_{1,2}(M_X) &= 0.06\\
\sqrt{2}\langle S\rangle &= 2.7\,\mathrm{TeV}\\
M_{1/2} &= 388\,\mathrm{GeV}\\
m_0 &= 681\,\mathrm{GeV}\\
A_0 &= 645\,\mathrm{GeV}
\end{aligned}$$



- $\kappa_1 = \kappa_2 \neq \kappa_3$ so degeneracy of Ds is lifted.
- lightest exotic quark is 300 GeV

“Late Discovery” Benchmark 4

$$
\begin{aligned}
\tan\beta &= 30\\
\lambda_3(M_X) &= -0.3847\\
\lambda_{1,2}(M_X) &= 0.1\\
\kappa_{1,2,3}(M_X) &= 0.1579\\
\sqrt{2}\langle S\rangle &= 5\,\mathrm{TeV}\\
M_{1/2} &= 725\,\mathrm{GeV}\\
m_0 &= 1074\,\mathrm{GeV}\\
A_0 &= 1726\,\mathrm{GeV}
\end{aligned}
$$



- $\kappa_1 = \kappa_2 = \kappa_3$ so Ds are degenerate (1612 GeV)
- lightest exotic squark is 312 GeV (due to large mixing)

Z' Decays

The U(1)$_N$ Z' has two differences compared to the sequential Z':

- The couplings are given by the U(1)$_N$ charges, so different to those of the SM Z-boson
- The Z' may decay to exotic matter, altering the width and Branching Ratios

Z'_N partial width [GeV]	BMC	BM4
$\Gamma(Z'_N \to l^+l^-)$ ($l = e, \mu$ or τ)	0.41	0.77
$\Sigma_l \Gamma(Z'_N \to \nu_l \overline{\nu}_l)$ (all neutrinos)	0.87	1.64
$\Sigma_l \Gamma(Z'_N \to l^+l^-, \nu_l \overline{\nu}_l)$ (all leptons)	2.10	3.96
$\Sigma_q \Gamma(Z'_N \to q\bar{q})$ (all quarks)	5.31	10.08
$\Sigma_i \Gamma(Z'_N \to D_i \bar{D}_i)$ (exotic fermions)	3.49	0.00
$\Sigma_\alpha \Gamma(Z'_N \to \tilde{H}_\alpha \tilde{H}_\alpha)$ (inert Higgsinos)	3.09	5.19
$\Sigma_\alpha \Gamma(Z'_N \to \tilde{S}_\alpha \tilde{S}_\alpha)$ (singlinos)	4.05	7.63
$\Sigma_i \Gamma(Z'_N \to \tilde{D}_i \tilde{D}_i)$ (exotic scalars)	0.00	0.19
$\Sigma_f \Gamma(Z'_N \to \tilde{f} \tilde{f})$ (sfermions)	0.00	0.010
$\Sigma_\alpha \Gamma(Z'_N \to H_\alpha H_\alpha)$ (inert Higgses)	0.026	0.39
$\Sigma_j \Gamma(Z'_N \to \tilde{\chi}_j \tilde{\chi}_j)$ (gauginos)	6.50×10^{-4}	7.92×10^{-5}
Γ_{tot} (all)	18.07	27.45

Example Decay:

$$Z' \to \tilde{S}_2 \tilde{S}_2$$

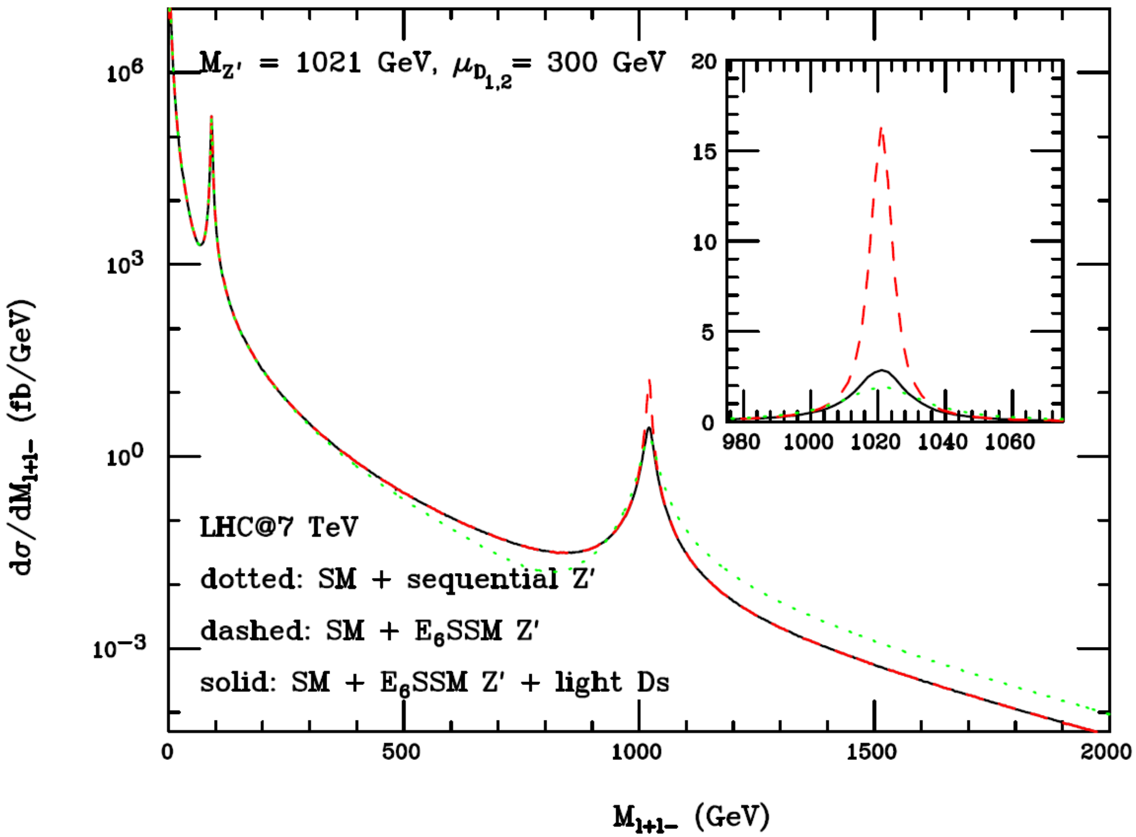
$$\hookrightarrow \bar{f} f \tilde{S}_1$$

$$\hookrightarrow \bar{f} f \tilde{S}_1$$

[Here we have set the singlino masses to 10 and 30 GeV]

Z' Line Shape

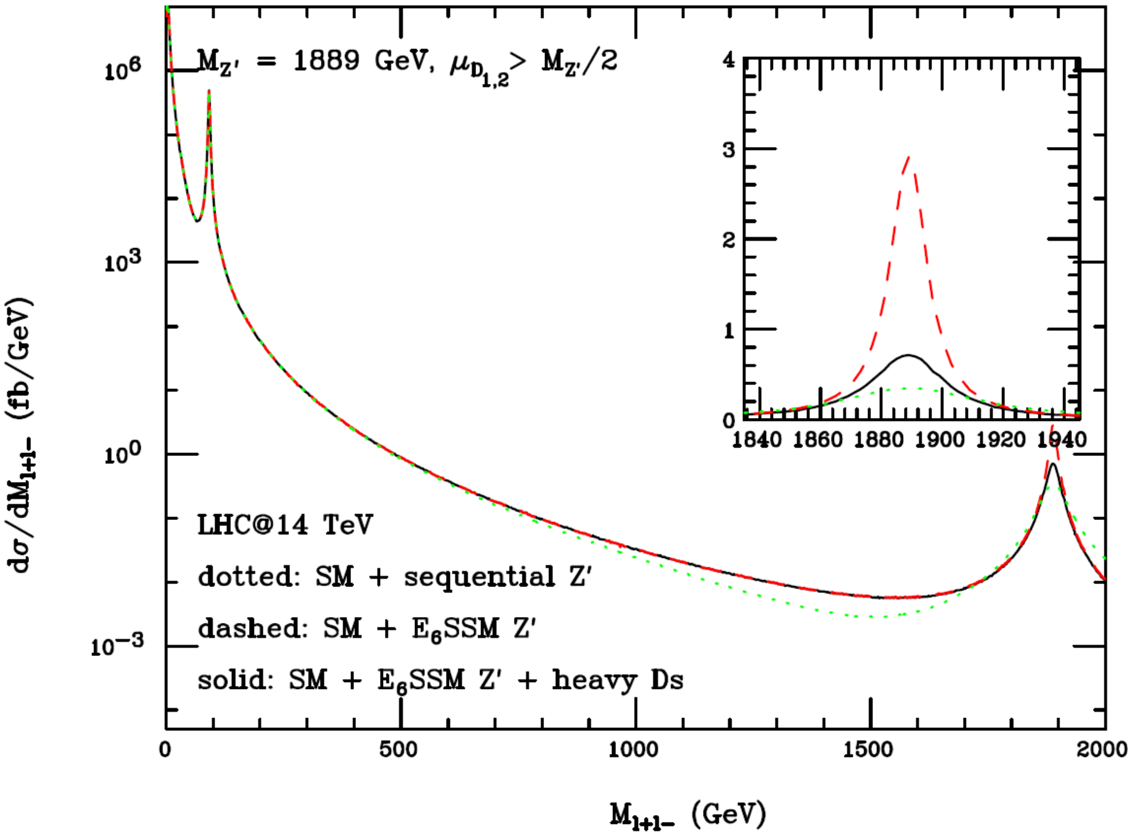
Benchmark C



Z' width increases from $\approx$ 7 GeV to $\approx$ 18 GeV when exotic matter is included.

Z' Decays

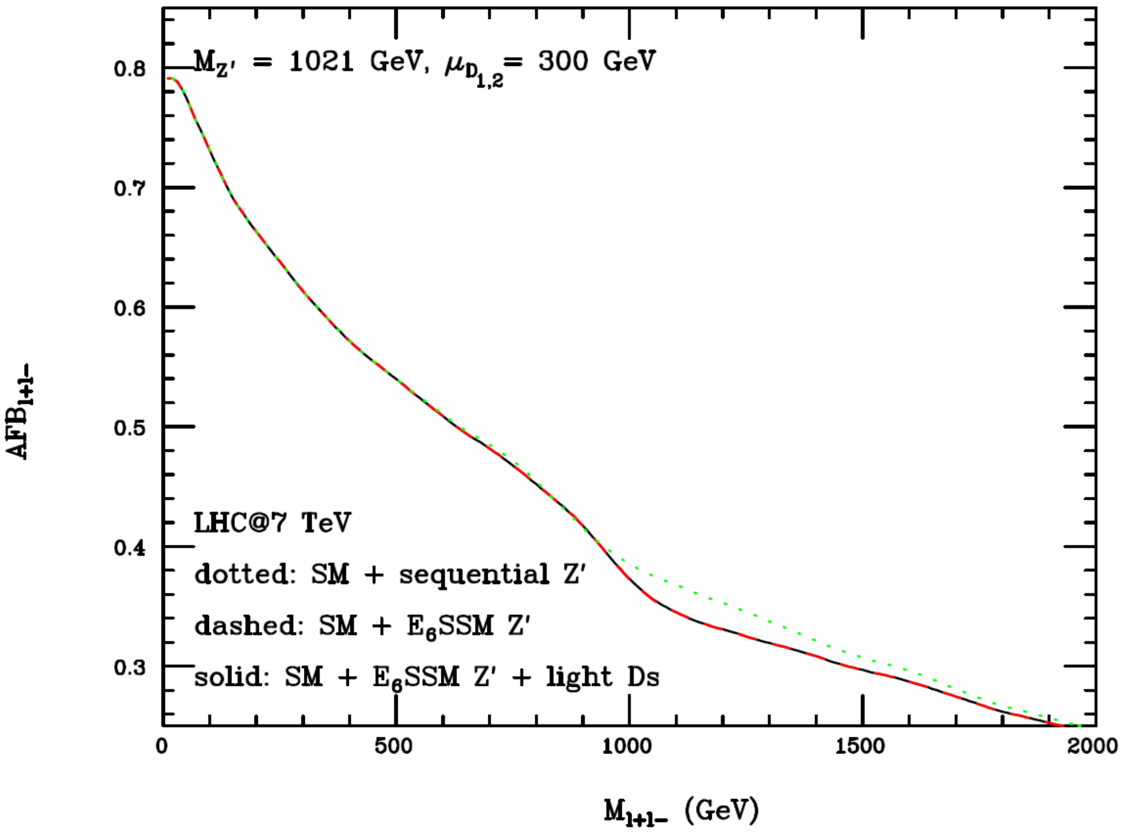
Benchmark 4



Note that this is now a 14 TeV LHC.

Z' Forward-backward asymmetry

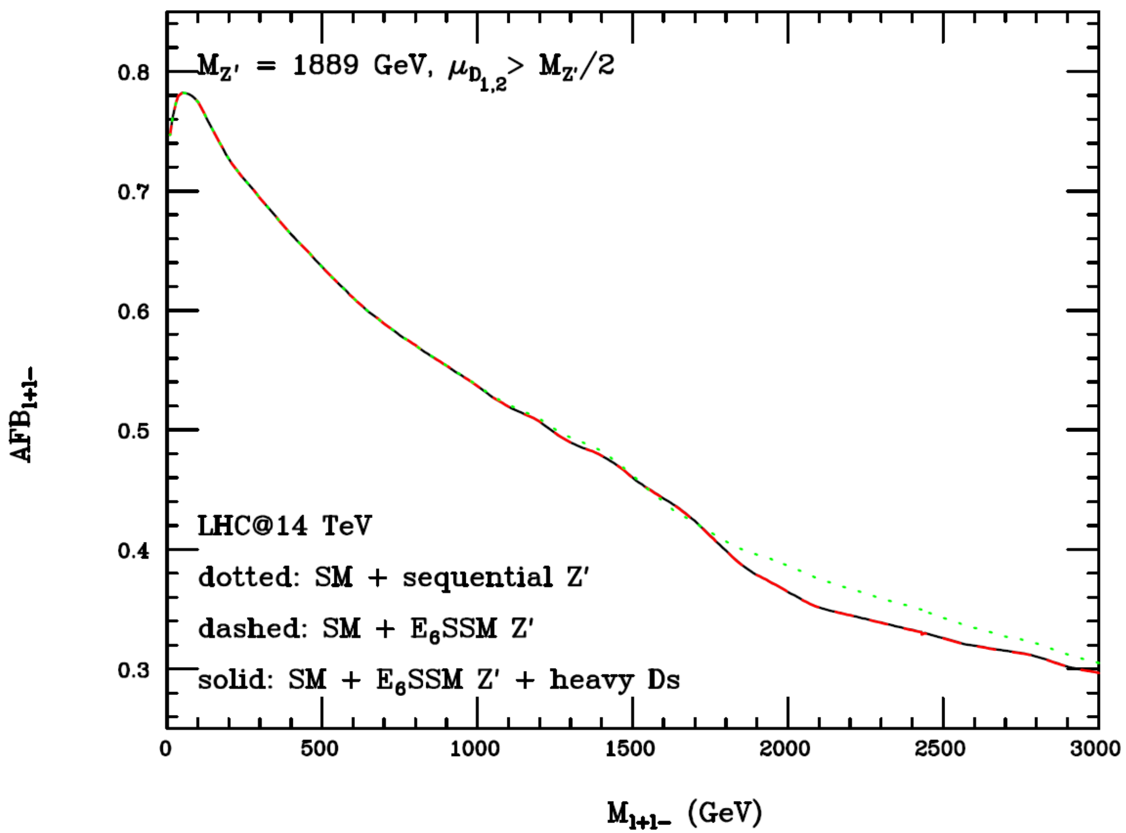
Benchmark C



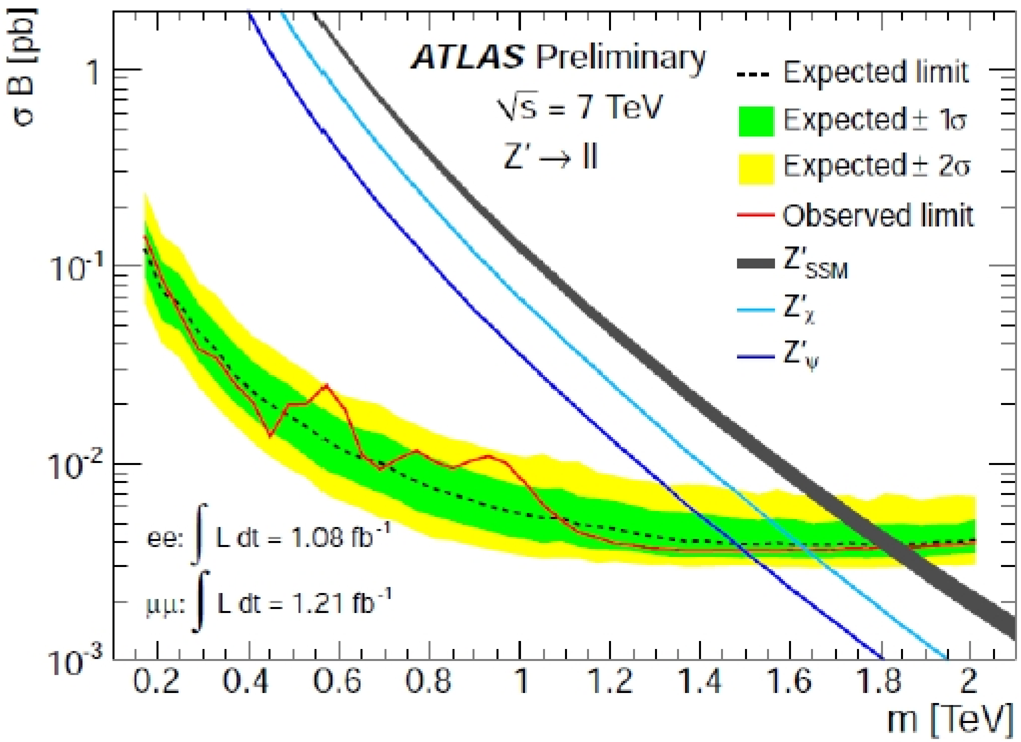
Notice that this is independent of the exotic content of the model.

Z’ Forward-backward asymmetry

Benchmark 4



LHC Z' exclusion limits



[Talk of Berger-Hryn'ova at EPS 2011]

LHC Z' limits are hard to interpret for the E_6SSM.

LHC limit $M_{Z'_N} \gtrsim 1520\,\text{GeV}$

(not shown on plot)

BMC has $M_{Z'} = 1021\,\text{GeV}$

BM4 has $M_{Z'} = 1889\,\text{GeV}$

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LHC Z' exclusion limits

But this isn't our Z'_N since it does not include the exotic matter.

We have already seen that Z'_N decays to exotic matter can substantially reduce the BR to leptons and weaken this limit.

BMC has $BR_{l^+l^-} = 0.023$

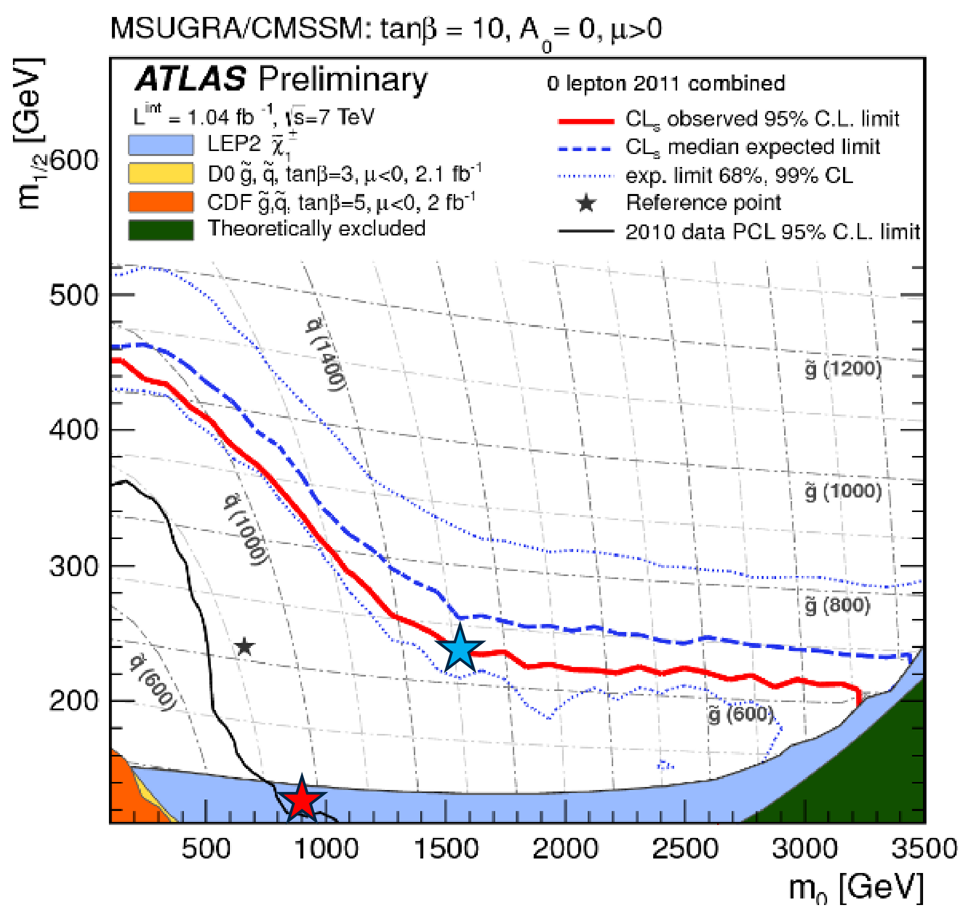
BM4 has $BR_{l^+l^-} = 0.028$

This can be compared to the Branching ratio if we neglect exotics: $BR_{l^+l^-} = 0.055$ (both benchmarks)

Using the Z'_ψ line on the previous slide and estimating the effect of reducing the branching ratio we can estimate that the limit changes to $\gtrsim 1300\,\mathrm{GeV}$

So BMC is almost certainly ruled out by this measurement, but BM4 is not.

LHC Squark and Gluino Limits



[Talk of Dave Charlton at EPS 2011]

There has been no LHC analysis for squarks and gluinos in the E_6SSM but we can use cMSSM limits to try and gain some insight.

BMC: $m_{\tilde{q}_L} = 929$ GeV, $m_{\tilde{g}} = 353$ GeV

BM4: $m_{\tilde{q}_L} = 1595$ GeV, $m_{\tilde{g}} = 642$ GeV

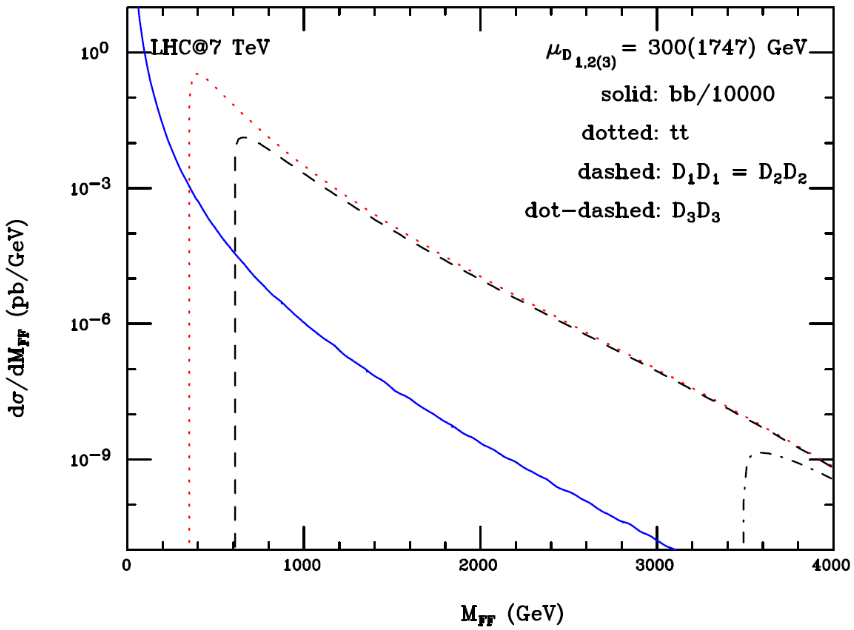
BMC looks ruled out while BM4 looks close to exclusion.

But remember that this is not an E_6SSM analysis (and uses different parameters), so it is too early to rule out BM4!

Exotic D-fermion production

Since the exotic quarks are colored, their production cross-sections are very large

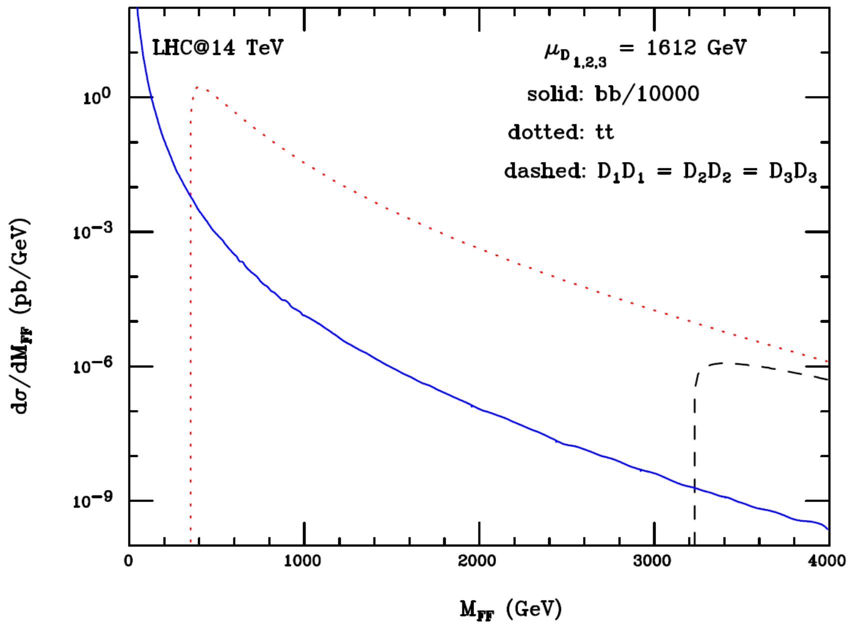
Benchmark C



$$\sigma(D_1D_1) = \sigma(D_2D_2) = 3\,\text{pb}$$

$$\sigma(D_3D_3) = 0.0005\,\text{fb}$$

Benchmark 4



$$\sigma(D_1D_1) = \sigma(D_2D_2) = \sigma(D_3D_3) = 0.9\,\text{fb}$$

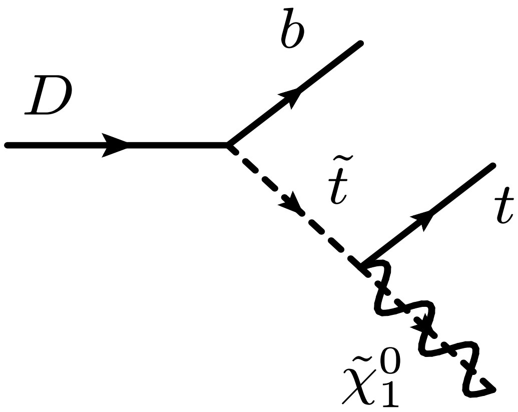
Exotic D-fermion decays

Decays of the exotic D-fermions are facilitated by the Z_2^H violating operators (that we set to be small earlier), e.g. $g_{ijk} D_i \left(Q_j Q_k \right)$

Assuming Ds couple predominantly to the 3rd generation:

Diquarks decay to $\tilde{t}b,\ t\tilde{b},$ so would give an enhancement to

$$pp \to t\bar{t}b\bar{b} + E_T^{miss} + X$$



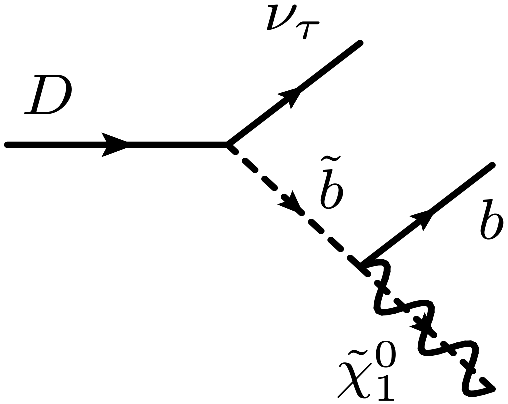
If the Z_2^H violating coupling is very small, D quarks may hadronize before they decay leading to spectacular signatures.

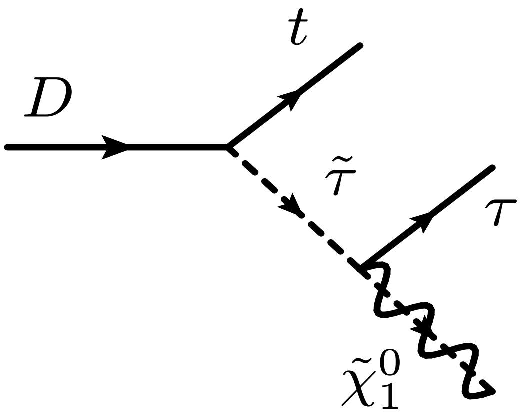
Exotic D-fermion decays

Leptoquarks decay to $\tilde{t}\tau,\ t\tilde{\tau},\ \tilde{b}\nu_\tau,\ b\tilde{\nu}_\tau$ so give enhancements to

$$pp \to t\bar{t}\tau^+\tau^- + E_T^{miss} + X$$

$$pp \to b\bar{b} + E_T^{miss} + X$$





Notice that SM production of $t\bar{t}\tau^+\tau^-$ is suppressed by $(\alpha_W/\pi)^2$ in comparison to $t\bar{t}$.

Exotic scalars and Inert Higgs

In BM4 the exotic scalars $\tilde{D}$ are rather light (due to mixing): $m_{\tilde{D}_{1,2}} = 312\,\mathrm{GeV}$

Note that these are $Z_2^{B/L}$ even, so don't need to decay to the LSP.

The Tevatron rules out the scalar diquarks lighter than about 630 GeV and scalar leptoquarks lighter than about 300 GeV, so these would need to be the leptoquarks.

Production cross-sections are $\approx$ 0.53 pb and $\approx$ 4.9 pb at a 7 TeV or 14 TeV LHC respectively.

They give an enhancement to, e.g. $pp \to t\bar{t}\tau\bar{\tau} + X$

Inert Higgs decays are similar to their MSSM counterparts

$$H^0_{1,i} \to b\bar{b} \qquad H^-_{1,i} \to \tau\bar{\nu}_\tau$$

$$\tilde{H}^0_i \to t\tilde{\bar{t}}^* \qquad \tilde{H}^0_i \to \tau\tilde{\bar{\tau}}^* \qquad \tilde{H}^+_i \to t\tilde{\bar{b}}^* \qquad \tilde{H}^-_i \to \tau\tilde{\bar{\nu}}^*_\tau$$

Conclusions and Summary

- The E_6SSM provides an example of a model which could arise from a GUT, where each generation forms a complete 27-plet of E_6.
- We have examined a constrained E_6SSM, using RGEs to construct realistic benchmark scenarios at LHC energies.
- The model predicts a light gluino, much lighter than the squarks, new exotic quarks and squarks, "inert" Higgs bosons, and a Z'.
- Already LHC results have ruled out our "early discovery" benchmark with limits from Z' production and squark/gluino production, but other benchmarks are still very viable.
- If the new exotic quarks are light, they will give striking signatures, such as a significant enhancement to $pp \to t\bar{t}b\bar{b} + E_T^{miss} + X$ which should soon be observable at the LHC.